Naval Research Laboratory
Stennis Space Center, MS 39529-5004

AD-A267 600

NRL/MR/7173--93-7038

Transient Signal Detection and Time Delay Estimation Using Higher Order Correlations and Spectra

L. A. PFLUG
R. L. FIELD

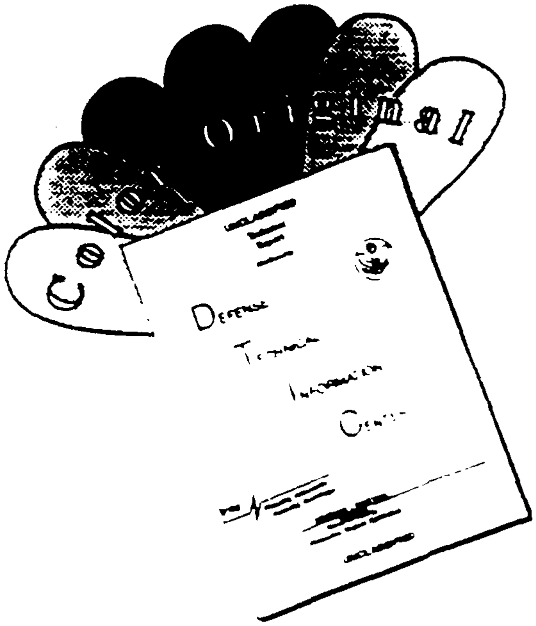
Ocean Acoustics Branch
Center for Environmental Acoustics

G. E. IOUP
J. W. IOUP

Department of Physics
University of New Orleans
New Orleans, LA 70148

June 1993

DISCLAIMER NOTICE



THIS DOCUMENT IS BEST QUALITY AVAILABLE. THE COPY FURNISHED TO DTIC CONTAINED A SIGNIFICANT NUMBER OF COLOR PAGES WHICH DO NOT REPRODUCE LEGIBLY ON BLACK AND WHITE MICROFICHE.

REPORT DOCUMENTATION PAGE

Form Approved
OBM No. 0704-0188

1. Agency Use Only *(Leave blank).*

2. Report Date. June 1993

3. Report Type and Dates Covered. Final

4. Title and Subtitle.
Transient Signal Detection and Time Delay Estimation Using Higher Order Correlations and Spectra

5. Funding Numbers.

Program Element No.	0601153N
Project No.	03208
Task No.	3A0
Accession No.	DN259125
Work Unit No.	73-5056-03

6. Author(s).
L.A. Pflug, R.L. Field, G.E. Ioup*, and J.W. Ioup*

7. Performing Organization Name(s) and Address(es).
Naval Research Laboratory
Center for Environmental Acoustics
Stennis Space Center, MS 39529-5004

8. Performing Organization Report Number.
NRL/MR/7173--93-7038

9. Sponsoring/Monitoring Agency Name(s) and Address(es).
Naval Research Laboratory
Systems, Support, and Requirements
Stennis Space Center, MS 39529-5004

10. Sponsoring/Monitoring Agency Report Number.
NRL/MR/7173--93-7038

11. Supplementary Notes.
*University of New Orleans
New Orleans, LA 70148

12a. Distribution/Availability Statement.
Approved for public release; distribution is unlimited.

12b. Distribution Code.

13. Abstract *(Maximum 200 words).*

This memorandum report contains a current summary of the authors' research on detection and time delay estimation for acoustic or other transients for which only one short-time realization exists. Thus, an energy signal model is used, rather than a power signal model. The energy signal model is more realistic for a brief transient, such as might be generated by a tool dropping on a metal floor or the return of an active sonar ping. Performance analysis is done for detection and time delay estimation of these transients embedded in Gaussian noise over a domain of signal-to-noise ratios. Monte Carlo simulations and hypothesis testing are used to generate receiver operating characteristic (ROC) curves to compare higher order and ordinary correlation detector and time delay estimator performance. Results indicate that for signals of high skewness and kurtosis, the higher order methods significantly outperform the cross correlation detector and time delay estimator. For signals of low skewness and kurtosis, rectification before detection often improves higher order detection to levels comparable to or even surpassing that of the cross correlator. For both signal classes, if the signal passband is approximately known, prefiltering prior to detection significantly improves higher order correlator performance. In the active sonar case, the higher order correlators with prefiltering can outperform the matched filter by more than 4 dB. Even larger improvements are observed in the passive case.

14. Subject Terms.
Altimetry, Mesoscale Oceanography, Ocean Forecasting

15. Number of Pages. 25

16. Price Code.

17. Security Classification	18. Security Classification of Report.	19. Security Classification of This Page.	20. Limitation of Abstract. of Abstract.
Unclassified	Unclassified	Unclassified	SAR

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102

CONTENTS

Overview	1
I. Introduction	3
II. Summary of Detection Results	3
A. Passive	3
B. Active	5
III. Summary of Time Delay Estimation Results	6
IV. Mathematical Properties of Higher Order Correlations and Spectra	7
Acknowledgments	9
References	10
Appendix	12

Transient Signal Detection and Time Delay Estimation
Using
Higher Order Correlations and Spectra

Overview

This research deals with detection and time delay estimation (TDE) for acoustic or other transient signals for which only one short-time realization exists. The transient is modeled as an energy signal, which is a time-limited signal with negligibly small amplitude values except in some finite region of the time scale, e.g., a pulse. In contrast, power signals are not time-limited and have non-negligible amplitudes over an infinite time scale, e.g., an infinite duration sinusoid. The energy signal model is more realistic than a power signal model for a brief transient, such as might be generated by a tool dropping on a metal floor or the return of an active sonar ping. The approach can be applied to deterministic transients or to a single realization drawn from an ensemble of energy signals. It can model known or unknown sources and also signals degraded by propagation distortion, such as multipath. To our knowledge we are the only group doing in-depth studies and publishing results for ordinary and higher order correlation detection and time delay estimation using an energy signal model.

Performance analysis is done for detection and TDE of these transients embedded in noise over a domain of signal-to-noise ratios (SNR's). Thus far only Gaussian distributed random noise has been used. It is a straightforward matter to substitute any type of noise into the simulations, however. Monte Carlo simulations and hypothesis testing are used to generate receiver operating characteristic (ROC) curves to compare higher order and ordinary correlation detectors and time delay estimator performance. The time domain parabolic equation (TDPE) model is used to simulate the effects of bottom-limited ocean environments on the signal.

Two classes of signals are considered, oscillatory transient signals characterized by low skewness and kurtosis and pulse-like transient signals characterized by high skewness and kurtosis. The work summarized here quantifies the terms high and low. For signals of high skewness and kurtosis the higher order methods significantly outperform the cross correlation detector and time delay estimator. For signals of low skewness and kurtosis, rectification before detection often improves higher order detection to levels comparable to or even surpassing that of the cross correlator. For both signal classes, if the passband is known, prefiltering prior to detection, as proposed by the authors, significantly improves higher order correlator performance. Preliminary investigations show that in the active case, with prefiltering, higher order correlators can outperform the matched filter by more than 4 dB. Even larger improvements are observed in the passive case.

The significant results from this research are:

(1) Higher order correlators offer considerable detection and time delay estimation advantages over the cross correlator provided the skewness/kurtosis of the signal is sufficiently high.

(2) For low skewness and kurtosis signals, rectification often improves performance of higher order correlators to equal, and in some cases, surpass that of the cross correlator. Rectification seldom hurts higher order detector performance. Therefore higher order methods used with rectification can usually outperform the cross correlator for high skewness and kurtosis signals and equal or possibly surpass it for low skewness and kurtosis signals.

(3) The dependence of higher order performance on signal skewness and kurtosis offers the possibility of developing higher order performance prediction capability without the necessity of doing computer intensive ROC curve analysis. The skewness and kurtosis parameters have been adequately predicted by the TDPE propagation model; therefore the environmental dependence of higher order performance can be determined over large ocean volumes.

(4) Preliminary investigations have shown that, when the signal passband is at least approximately known, prefiltering enables the higher order detector to significantly outperform the matched filter for most signals.

I. Introduction

Under the ONR 6.1 Acoustic Transients ARI (1988 - 1992), NRL has been researching the feasibility of applying higher order correlations and spectra to the detection and time delay estimation of bandlimited acoustic transients. This research deals specifically with transient signals for which only one, short-time, realization is available for detection and time delay estimation. The main focus of the research has been to compare higher order correlation and spectral detectors and higher order correlation time delay estimators to the ordinary cross correlation detector and time delay estimator for passive and active sonar in a Gaussian noise environment.

Additional signal processing problems addressed include finding the signal properties that determine how higher order time domain and frequency domain techniques perform, and determining the effects of signal rectification as part of higher order detection and time delay estimation algorithms.

Another major research component of the Acoustic Transients ARI at NRL Stennis has been the development of the time domain parabolic equation (TDPE) model. This model has been shown to simulate accurately the broadband ocean impulse response from which critical signal features can be extracted and mapped over range and depth in the ocean. The signal processing research coupled with broadband modeling and experimental measurements has allowed the development of a performance prediction capability of ordinary and higher order methods in bottom-limited ocean environments.

The definitions of higher order correlations and spectra are given in the Mathematical Properties section. In the following summaries, the term passive is used when there is no a priori knowledge of the transmitted signal. In this case, the term x_0 in the higher order correlations or the term X_0^* in the higher order spectra include independent noise, as do the other terms. The term active is used when the source is known. In this case the above terms are the source replicas and contain no noise.

II. Summary of Detection Results

A. Passive

During this research, it has been found that for passive sonar, where there is no a priori knowledge of the signal, higher order correlation threshold detectors, i.e., the bicorrelation and tricorrelation detectors, perform better than the cross correlation detector for signals of high skewness and kurtosis in the presence of Gaussian noise. Figures 1a and 1b (see the Appendix) show the time waveform and spectrum, respectively, of such a signal. Conversely, other researchers have shown higher order frequency domain techniques, i.e., the bispectrum and trispectrum detectors perform better than the energy detector for narrowband signals that might have low values of skewness and kurtosis. The frequency domain techniques have been more widely studied since they can also be easily applied to tonal or power signals embedded in Gaussian noise. In contrast, our research has focused on the time domain applications appropriate for short-time duration energy signals. Detection results have been documented in journal articles, three proceedings articles, and three abstracts. See numbers [2], [3], [6], [7], [8], [9], [12], [13], and [14] in References.

For energy transients, bicorrelation and tricorrelation threshold detection performance depends on several factors including the sampling rate, the observation time, and the signal skewness and kurtosis. Monte Carlo computer simulations and hypothesis testing have been used to generate receiver operating characteristic (ROC) curves to compare correlation detector performance. For example, the narrow-time pulse of Figure 1a has a skewness of 15.71 and a kurtosis of 262.643. The ROC curve simulations shown in Figure 2 indicate that for the signal shown in Figure 1a, the ordinary correlation is the worst detector for passive sonar. The ROC curves of Figure 2 have a probability of false alarm of 0.001.

It has been shown that the performance of the bicorrelation and tricorrelation detectors is related to the skewness and kurtosis, respectively, of the signal. Figures 3a and 3b are general prediction curves showing the gain in signal-to-noise (SNR) the bicorrelation and tricorrelation detectors have over the cross correlator as a function of signal skewness and kurtosis. The computer simulated curves are calculated by taking the difference in SNR between the higher order detectors and the cross correlator at a probability of detection, P_d, of 0.5 and for a fixed probability of false alarm, P_{fa}. The curves show that for 2048 sample points and $P_{fa} = 0.001$, the bicorrelation detector will show greater gain than the cross correlation detector for signals with minimum skewness of 3.42, and the tricorrelation detector will show greater gain for signals with a minimum kurtosis of 9.64. (See dashed lines in Figures 3a and 3b). These results are included in a journal article currently in preparation, reference [6]. Theoretical prediction formulas are currently being developed.

As indicated by the prediction curves of Figures 3a and 3b, higher order methods may not perform as well as the cross correlator for many oscillatory signals with relatively low skewness and kurtosis. This problem can be alleviated by using signal rectification. As an example of the effects of signal rectification on higher order detection, two signals are considered, an FM linear sweep shown in Figures 4a and 4b (skewness = -5.80 x 10-7, kurtosis = 3.14) and the 49 - 51 Hz sinusoid shown in Figure 5a and 5b (skewness = 0.34, kurtosis = 18.0). P_d versus SNR curves are shown in Figure 6 for the FM sweep both without and with rectification. Figure 6 shows that the bicorrelation detector gives very poor performance and that the cross correlator outperforms the tricorrelator by about 2 dB when no signal rectification is used. However, with rectification the bicorrelator is comparable to the unrectified cross correlator and the tricorrelator outperforms it by about one dB at a P_d of 0.5. For this signal, rectification causes cross correlator performance to degrade while significantly improving higher order performance. P_d versus SNR curves for the 49 - 51 Hz sinusoid of Figure 4 are shown in Figure 7. Again, rectification greatly improves the performance of the bicorrelator but somewhat degrades performance of the tricorrelator for this signal. However, both of the rectified higher order correlators outperform the cross correlator. A general conclusion from the work on rectification is that it often improves higher order performance to equal or exceed cross correlator performance.

The prediction curves of Figures 3a and 3b can be used in conjunction with a broadband acoustic propagation model, such as the TDPE model, to produce maps that indicate environmental regions over which higher order correlations outperform the ordinary correlation. For example, Figure 8a shows a color TDPE simulation of the kurtosis of an experimental signal as a function of range and depth in a bottom-limited ocean of 915 m depth. The case modeled is taken from a transient experiment performed in the Atlantic. The transmitted pulse has a kurtosis of just over 100. From the prediction curve of Figure 3b, a tricorrelator detecting a signal with a kurtosis of 100 would be expected to have about a 4 dB gain over a cross correlator. The bottom-limited environment causes the pulse to undergo multipath propagation which decreases the kurtosis of the signal and therefore the performance of the tricorrelator. Figure 8a shows that a "kurtosis duct" is beginning to form at 11 km in range and between 50 and 100 m in depth. Beginning at this range and at these depths the kurtosis is back up and the gain of the tricorrelator is recovered. The "kurtosis duct" that is formed is not due to a sound speed duct. The sound speed profile at this site is completely downward refracting. Figure 8b shows the kurtosis predicted by TDPE Vs the measured kurtosis of the experimental signal as a function of range at a depth of 250 m.

The prediction curves shown in Figures 3a and 3b coupled with model simulations (Figure 8a) which accurately predict (Figure 8b) critical signal features offer the potential to evaluate higher order techniques for different signal types propagating in bottom-limited environments.

B. Active

For active sonar, where the transmitted signal is known, it has been shown by the authors that prefiltering can result in higher order correlation detectors giving better performance than the matched filter for most signals.

Prefiltering down to a known or estimated passband of the signal can be used to achieve SNR advantage when the signal is concentrated in frequency and the noise band is broader than the signal band. The matched filter used in active sonar is already possessed of this advantage and even gives shaping within the passband. While prefiltering should have little if any effect on the ordinary correlation detector for the known source case (matched filter), it can dramatically affect the bicorrelation and tricorrelation detectors for the known source case as shown by the P_d versus

SNR curve given in Figure 9 for the pulse of Figure 1a. Using the simplest interpretation of spectral volume as an indicator of detection performance, the one-dimensional correlation detection advantage can go as the ratio of the signal passband to the total bandwidth. However, for two-dimensional bicorrelation detection, the advantage can go as the square of the ratio of the signal passband to the total bandwidth, and for three-dimensional processing, it can go as the cube of the ratio. Other factors must be taken into consideration to determine the predicted performance advantage.

The P_d versus SNR curves in Figure 9 show, as expected, that the cross correlation detector is not affected by prefiltering. However, both higher order detectors show a significant improvement in performance over the unfiltered curves. At a P_d of 0.5 the prefiltered tricorrelator shows about a 2.5 dB gain over the unfiltered tricorrelator and about a 4 dB gain over the matched filter. Signals of higher skewness and kurtosis should show even greater improvement.

The performance of the tricorrelation detector for the 49 -51 Hz sinusoid can be greatly improved if the approximate signal passband is known and prefiltering is applied Figure 10 shows the change in performance if a 40 - 60 Hz bandpass filter is applied before detection. The bicorrelator performs poorly in both cases. At a P_d of 0.5, the cross correlator improves by more than 5 dB and the tricorrelator improves by 8 dB. Without prefiltering the tricorrelator outperforms the cross correlator by 2 dB at a P_d of 0.5. With prefiltering the tricorrelator outperforms the cross correlator by almost 5 dB at a P_d of 0.5. The tricorrelation SNR gain resulting from prefiltering is much greater than the SNR gain shown by ordinary correlation. Preliminary prefiltering results have been presented at the Fall 1992 Acoustical Society meeting (see [17] in References) and has been accepted for publication in a proceedings article (no. [10] in References).

III. Summary of Time Delay Estimation Results

Higher order correlation time delay estimation performance has been compared to ordinary correlation time delay estimation for energy transients in Gaussian noise using Monte Carlo computer simulations. Higher order methods using rectification are included in the study. Received signals from only two sensors are used in each correlation, i.e., the bicorrelation and tricorrelation contain repeated signals. Thus the tricorrelation method with rectification is equivalent to the tricorrelation method without rectification. It is found that using noise wraparound in the correlations of sufficiently long noisy energy signals not only avoids the estimation error that results from correlation bias, but reduces computational costs as well. This study was documented in a journal article and three abstracts: references [4], [11], [14], and [15].

For the passive sonar case where the source is unknown, the higher order methods can perform better than the cross correlation method. For instance, the probability of correct delay versus SNR shown in Figure 11 for the narrow pulse (see Figure 1) indicates that the cross correlation method is the least accurate in estimating the exact time delay, and has the highest standard deviation of delay estimates, as shown in Figure 12. The tricorrelation method performs most accurately, showing an SNR improvement of almost 7 dB over the cross correlation method for a 0.5 probability of correct delay, and the lowest standard deviation of delay estimates.

For the active sonar case, the ordinary correlation technique performs best if the environment contained no multipath. However, if multipath is present, the higher order methods can perform better than the ordinary correlation method for some signals (see reference [4]).

IV. Mathematical Properties of Higher Order Correlations and Spectra

Higher order correlations and spectra have been well defined for stationary power signals, but not for energy signals. One part of this research has been to develop useful higher order definitions for energy signals. The bicorrelation and tricorrelation are expressed as straightforward extensions of the one-dimensional correlation for energy signals as follows:

<u>Cross Correlation</u>

$$CC(\tau_1) = \int_{-\infty}^{+\infty} x_0(t)x_1(t+\tau_1)\,dt$$

<u>Bicorrelation</u>

$$BC(\tau_1,\tau_2) = \int_{-\infty}^{+\infty} x_0(t)x_1(t+\tau_1)x_2(t+\tau_2)\,dt$$

<u>Tricorrelation</u>

$$TC(\tau_1,\tau_2,\tau_3) = \int_{-\infty}^{+\infty} x_0(t)x_1(t+\tau_1)x_2(t+\tau_2)x_3(t+\tau_3)\,dt$$

The corresponding one, two, and three dimensional Fourier transforms of these energy signal definitions, the energy spectrum, the bispectrum, and the trispectrum, can be shown to be the same as those for power signals [1], and can be written as products of one-dimensional Fourier transforms:

Energy Spectrum

$$ES(f_1) = X_1(f_1)X_o^*(f_1)$$

Bispectrum

$$BS(f_1,f_2) = X_1(f_1)X_2(f_2)X_o^*(f_1+f_2)$$

Trispectrum

$$TS(f_1,f_2,f_3) = X_1(f_1)X_2(f_2)X_3(f_3)X_o^*(f_1+f_2+f_3)$$

Derivations of these expressions as well as the properties of higher order correlations and spectra of energy signals, especially bandlimited signals, are documented in references [1], [12], and [18].

The sampling criteria for the autobicorrelation and autotricorrelation calculated from discrete-time one-dimensional signals and their transforms as defined above are found to differ from the sampling criteria for sampling the continuous-time autobicorrelation and autotricorrelation and one-dimensional functions in general. That is, to avoid aliasing in a sampled signal, autocorrelation, or sampled continuous-time autobicorrelation or autotricorrelation, the Nyquist frequency must be chosen to be greater than or equal to the highest frequency present in the bandlimited signal. However, to avoid aliasing in the autobicorrelation and autotricorrelation calculated from discrete-time one-dimensional transients, the Nyquist frequency must be chosen to be greater than or equal to three-halves the highest frequency present in the original signal for the bicorrelation and twice the highest frequency present for the tricorrelation. This finding indicates that increased sampling rates, masking filters, or interpolation should be used for higher order applications, and has been documented in references [1], [5], [16], and [18].

Acknowledgments

The authors wish to express their appreciation to James L. Leclere, Naval Research Laboratory, Stennis Space Center, Grayson H. Rayborn, Dept. of Physics and Astronomy, University of Southern Mississippi, and Kenneth H. Barnes, University of New Orleans, for their contributions to this research. The authors also wish to acknowledge support and funding from ONR under the ONR 6.1 Acoustic Transients ARI, ONR/NRL Acoustics Transient Core Project # 71-5059-0-3, Program Element Number 651153N, Program Manager Dr. Edward R. Franchi, ONR/NOARL Grant No. N00014-89-J-6002, and NRL through the U.S. Navy ASEE Summer Faculty Research Program.

References

Refereed Journal Articles

[1] "Properties of Higher-Order Correlations and Spectra for Bandlimited Deterministic Transients", Lisa A. Pflug, George E. Ioup, Juliette W. Ioup, and Robert. L. Field, J. Acoust. Soc. Am., Vol. 91, 975-988 (1992).

[2] "Higher-Order Correlations for the Detection of Deterministic Transients", George E. Ioup, Lisa A. Pflug, Juliette W. Ioup, Kenneth H. Barnes, Robert L. Field, James H. Leclere, and Grayson H. Rayborn, U.S. Navy Jour. of Underwater Acoustics (JUA), 925-944 (1990).

[3] "Detection of Oscillatory and Impulsive Transients Using Higher-Order Correlations and Spectra", Lisa A. Pflug, George E. Ioup, Juliette W. Ioup, Kenneth H. Barnes, Robert L. Field, and Grayson H. Rayborn, J. Acoust Soc. Am., Vol. 91, 2763-2776 (1992).

[4] "Time Delay Estimation for Deterministic Transients Using Second and Higher-Order Correlations", Lisa A. Pflug, George E. Ioup, Juliette W. Ioup, and Robert. L. Field, accepted for publication in J. Acoust. Soc. Am., Sept., 1993.

[5] "Sampling Requirements and Aliasing for Higher Order Correlations", Lisa A. Pflug, George E. Ioup, and Juliette W. Ioup, accepted for publication in J. Acoust. Soc. Am., Oct., 1993.

[6] "Prediction of Higher Order Correlation Detector Performance for Bandlimited Energy Transients", L.A. Pflug, R.L. Field, G.E. Ioup, and J.W. Ioup, in preparation for J. Acoust. Soc. Am.

Proceedings

[7] " Higher Order Correlations for Transient Detection", George E. Ioup, Juliette W. Ioup, Robert L. Field, and James H. Leclere, Proceedings of the First Acoustic Transient Workshop Held at Naval Ocean Research and Development Activity, NSTL, Naval Res. Lab. Publ. 152-5100, 628-660 (1989).

[8] "Evaluation of Bicorrelations for Transient Detection", George E. Ioup, Juliette W. Ioup, Kenneth H. Barnes, Robert L. Field, James H. Leclere, and Grayson H. Rayborn, Proceedings of the Workshop on Higher-Order Spectral Analysis, Vail, CO (IEEE, New York), 46-51 (1989).

[9] "Higher-Order Correlations and Spectra and Detection and Time Delay Estimation for Deterministic Transients", Lisa A. Pflug, George E. Ioup, Juliette W. Ioup, Kenneth H. Barnes, Robert L. Field, James H. Leclere, and Grayson H. Rayborn, Proceedings of the Second Acoustic Transients Workshop held at NRL, Wash. D.C., 127-169 (1990).

[10] "Prefiltering for Higher Order Advantage", George E. Ioup, Lisa A. Pflug, Juliette W. Ioup, and Robert L. Field, Proceedings of the IEEE Signal Processing Workshop on Higher-Order Statistics, 309-313 (1993).

Abstracts

[11] "Comparisons of Double and Triple Cross Correlation for Arrival Time Identification of Amplitude and Frequency-Modulated Acoustic Transient Signals", Juliette W. Ioup, George E. Ioup, Robert L. Field, and James H. Leclere, J. Acoust. Soc. Am., Suppl1, Vol. 84, S17 (1988).

[12] "Higher-Order Correlations and Spectra and the Detection of Narrow Band Deterministic Transients", Lisa A. Pflug, Kenneth H. Barnes, George E. Ioup, Juliette W. Ioup, Robert L. Field, James H. Leclere, and Grayson H. Rayborn, J. Acoust. Soc. Am., Suppl1, Vol. 86, S118 (1989).

[13] "Effects of Environmental Degradation on Higher-Order Correlation Detectors for Deterministic Signals", Lisa A. Pflug, George E. Ioup, Juliette W. Ioup, Robert L. Field, and James H. Leclere ,J. Acoust. Soc. Am., Suppl. 1, Vol. 887 S155(1990).

[14] "Detection and Time-Delay Estimation for Band-Limited Transients Using Higher-Order Correlations", Lisa A. Pflug, George E. Ioup, Juliette W. Ioup, Robert L. Field, and Grayson H. Rayborn, J. Acoust. Soc. Am., Suppl. 1, Vol. 88, S29 (1990).

[15] "Time Delay Estimation for Deterministic Transients Using Second- and Higher-Order Correlations", Lisa A. Pflug, George E. Ioup, Juliette W. Ioup, Robert L. Field, and James H. Leclere, J. Acoust. Soc. Am., Vol. 90, 2366 (1991).

[16] "Aliasing and Sampling Criteria for Higher Order Correlations", Lisa A. Pflug, George E. Ioup, and Juliette W. Ioup, J. Acoust. Soc. Am., Vol. 92, 2417 (1992).

[17] "Prefiltering for Improved Correlation Detection of Narrow- and Medium-Band Energy Signals", George E. Ioup, Lisa A. Pflug, and Juliette W. Ioup, J. Acoust. Soc. Am., Vol. 92, 2417 (1992).

Other Documents

[18] "Higher Order Correlations and Spectra for the Detection of Deterministic Transients", Lisa A. Pflug, M.S thesis, University of New Orleans, Louisiana (1990).

[19] "Comments on 'Properties of Higher-Order Correlations and Spectra for Bandlimited Deterministic Transients' [J. Acoust. Soc. Am. 91, 975-988 [1992]", P. A. Nielsen, J. Acoust. Soc. Am., Vol. 92, 1763-1765 (1992).

Appendix

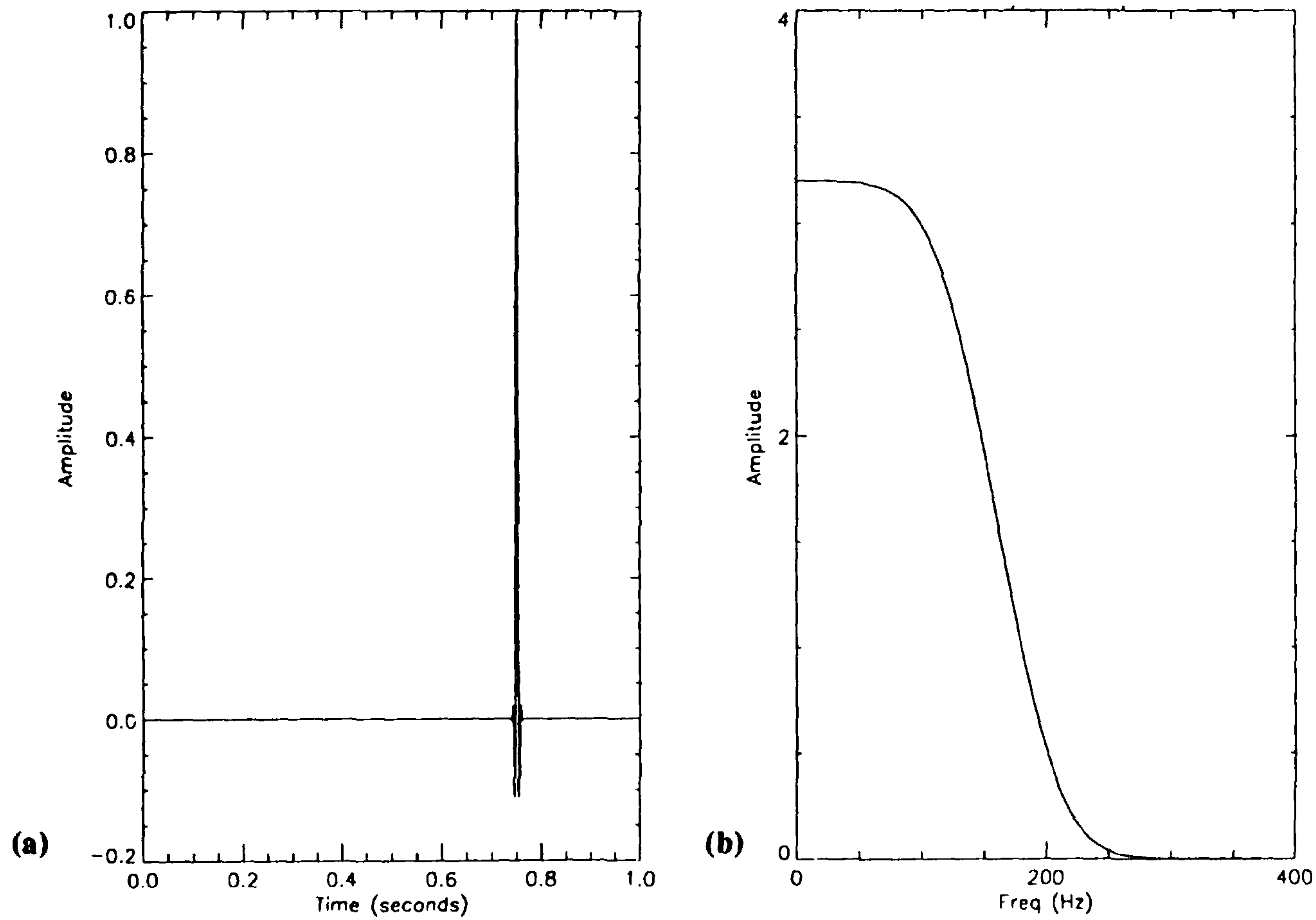


Figure 1. **(a)** Narrow pulse. **(b)** Fourier magnitude spectrum

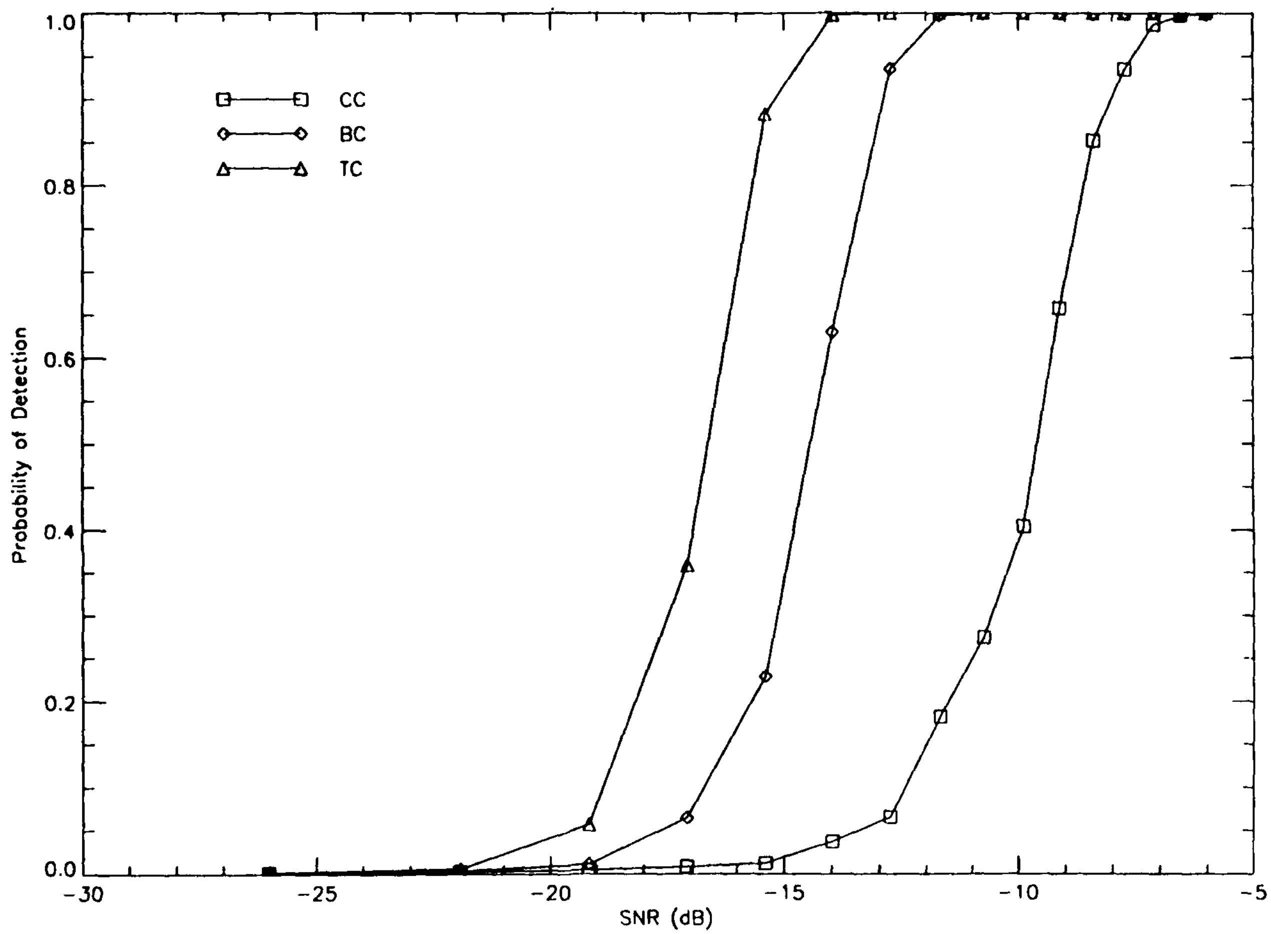


Figure 2. P_d versus SNR at $P_{fa} = 0.001$ for the narrow pulse and an unknown source model.

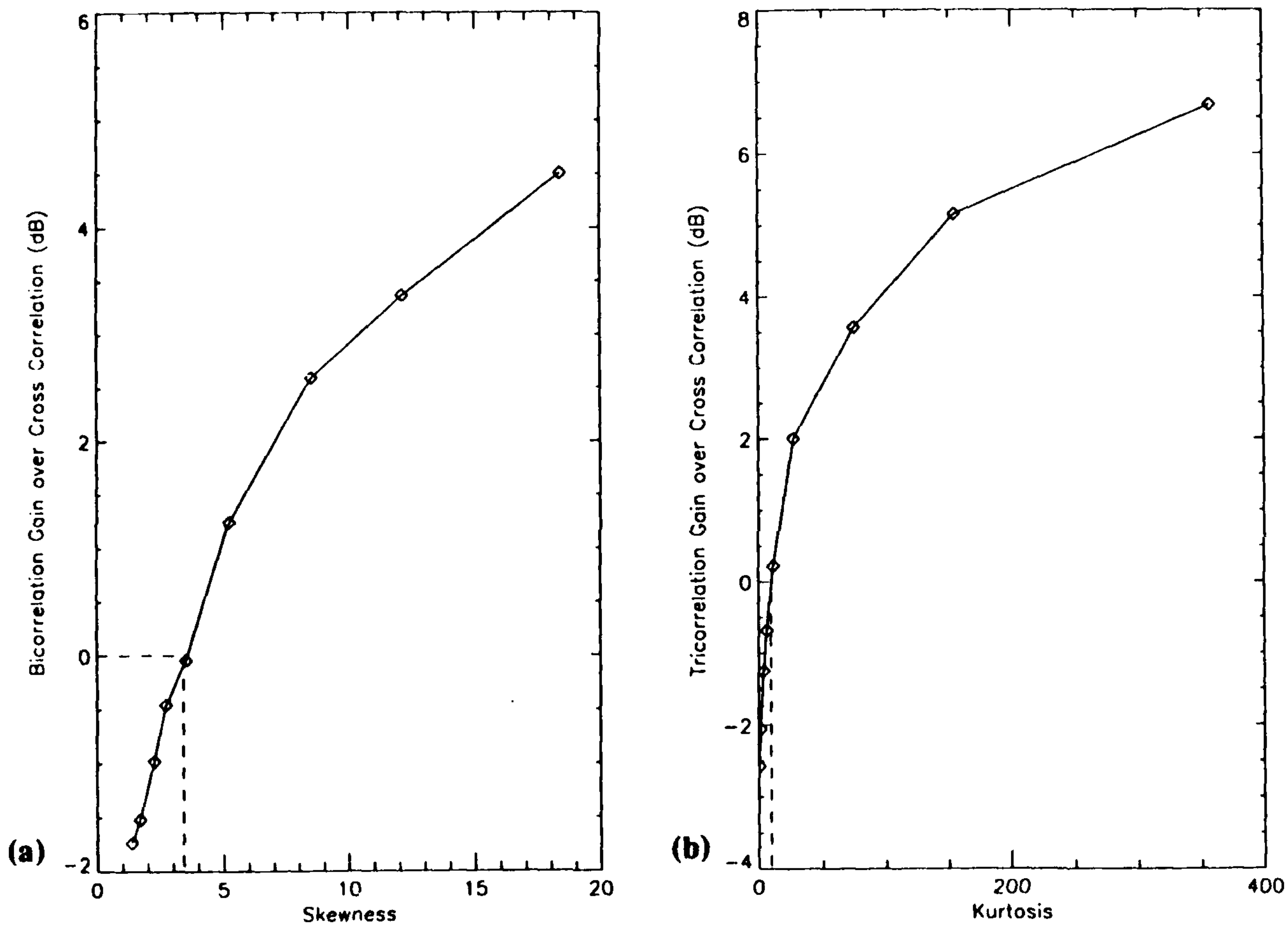


Figure 3. **(a)** Computer simulations of bicorrelation SNR gain versus signal skewness for 2048 sample points. **(b)** Computer simulations of tricorrelation SNR gain versus signal kurtosis for 2048 sample points.

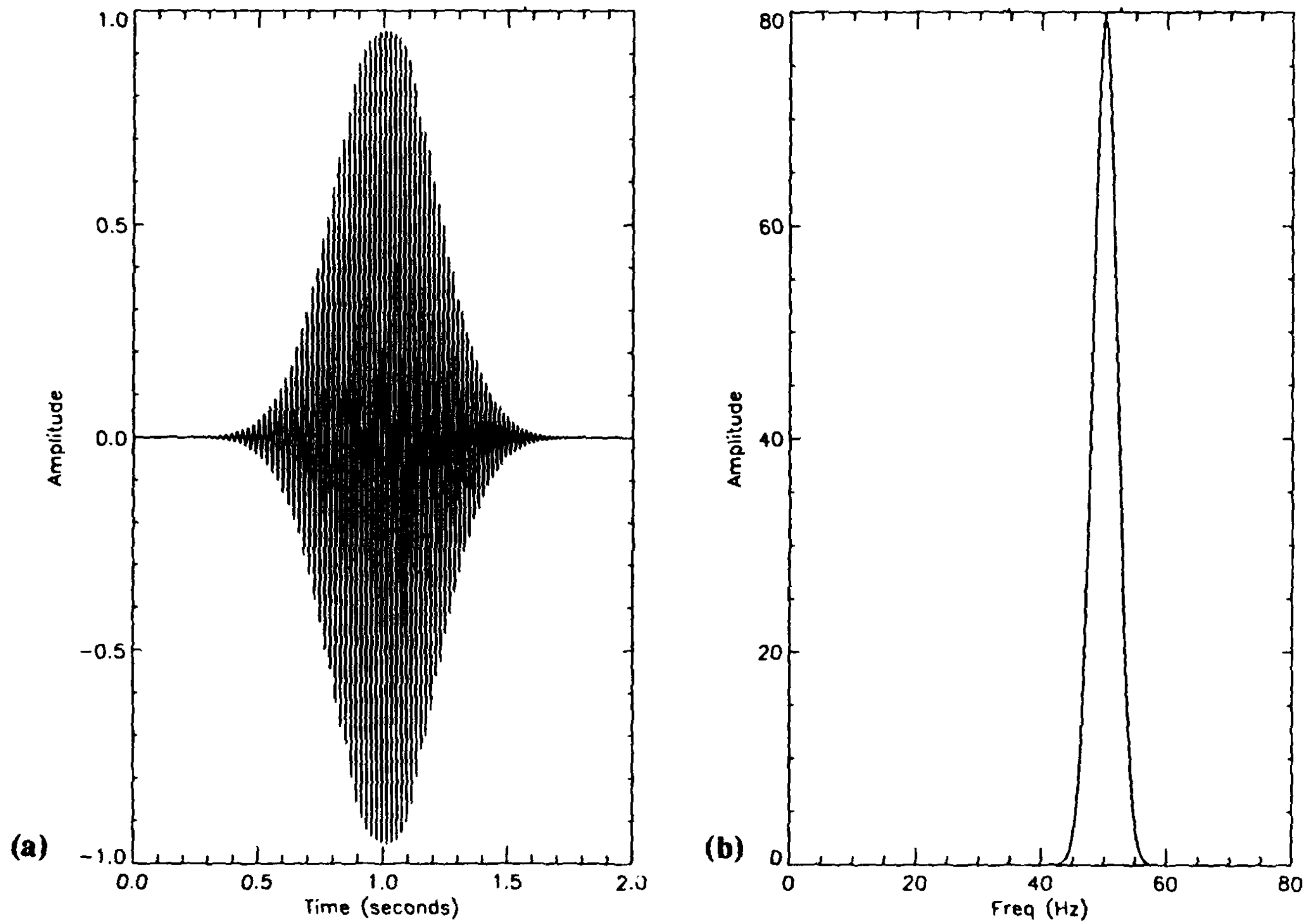


Figure 4. **(a)** 41 - 59 Hz FM linear sweep. **(b)** Fourier magnitude spectrum.

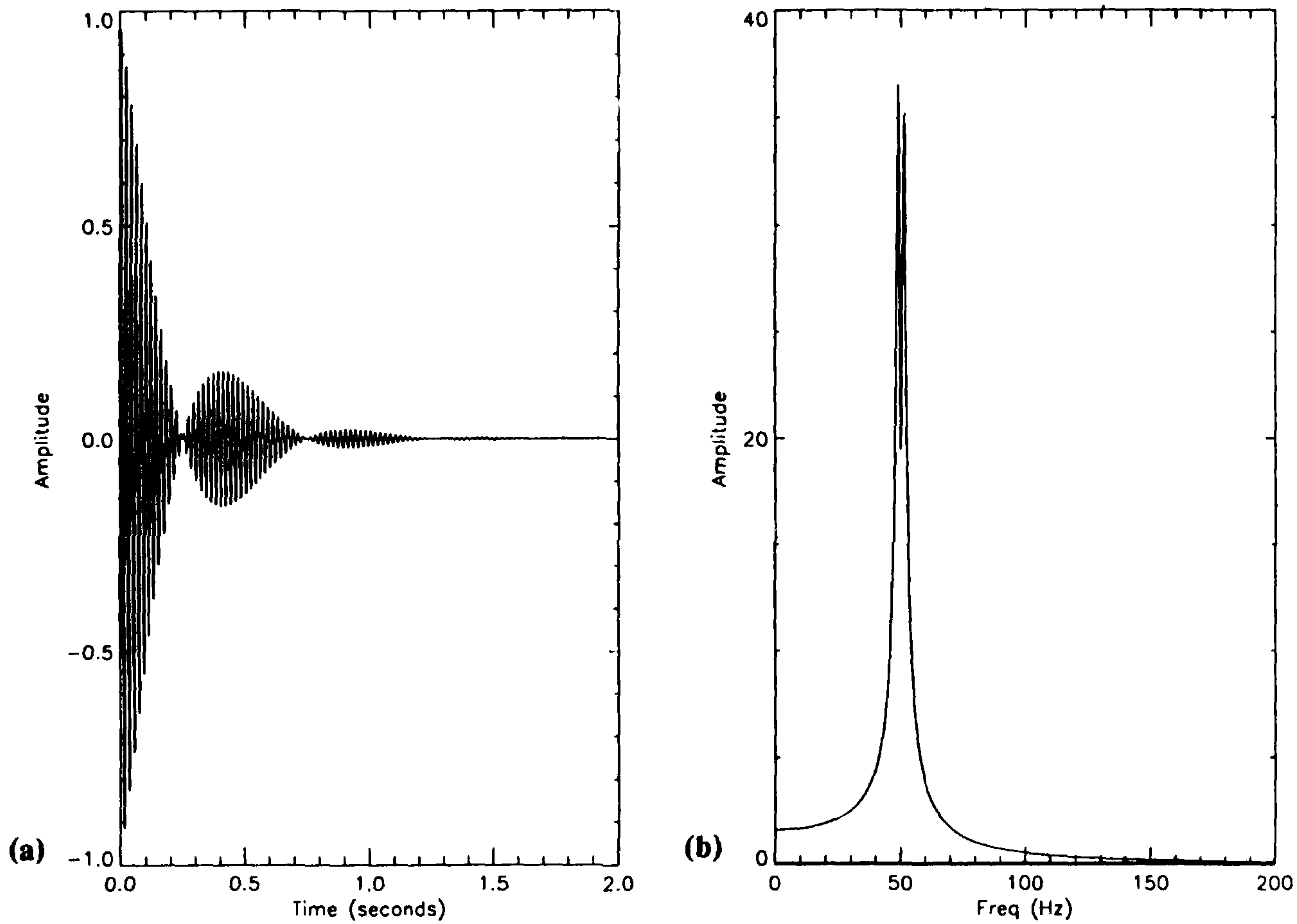


Figure 5. 49 - 51 Hz beating sinusoid. **(b)** Fourier magnitude spectrum.

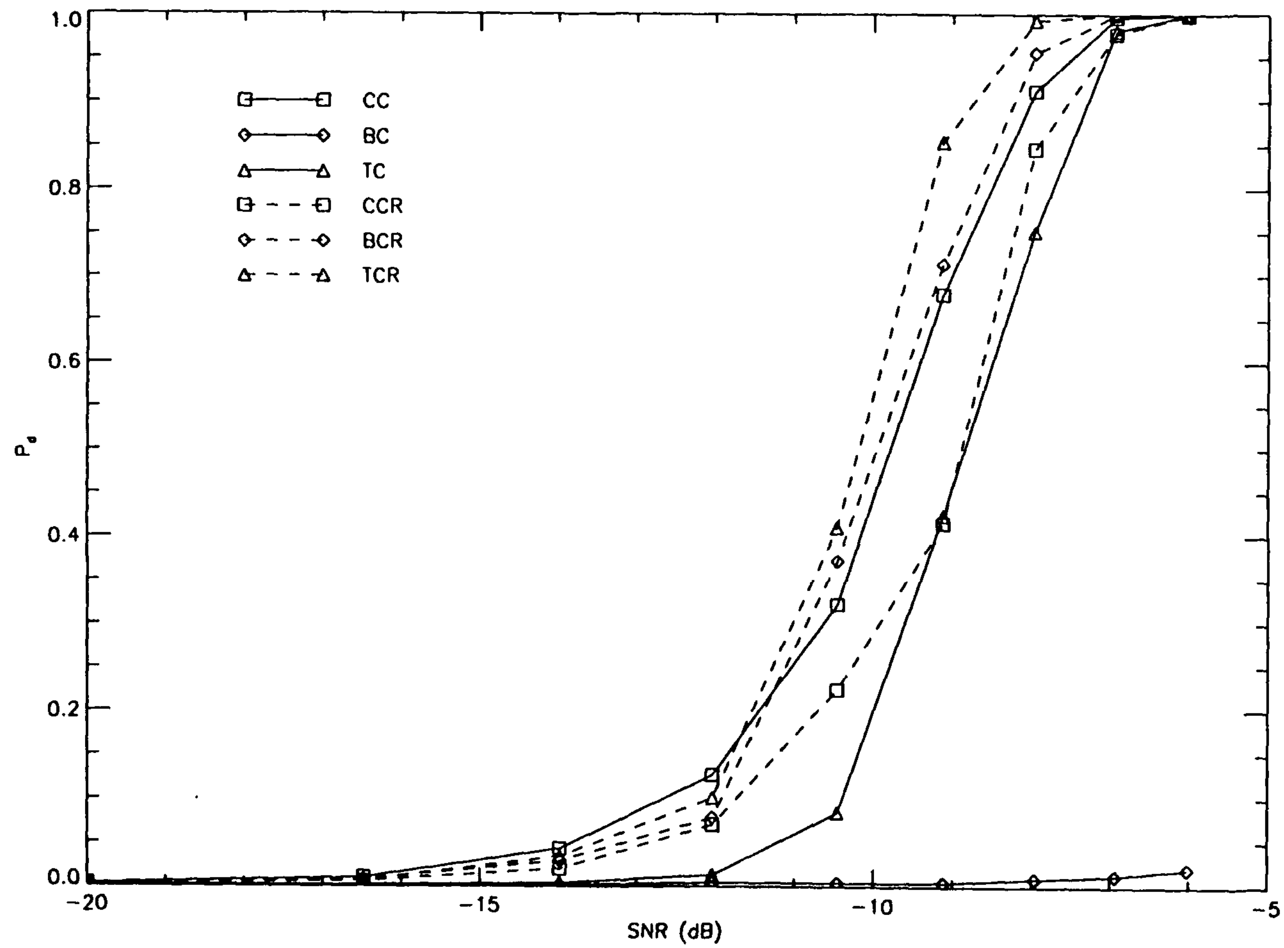


Figure 6. P_d versus SNR at $P_{fa} = 0.001$ for the 41 - 59 Hz FM linear sweep and an unknown source model.

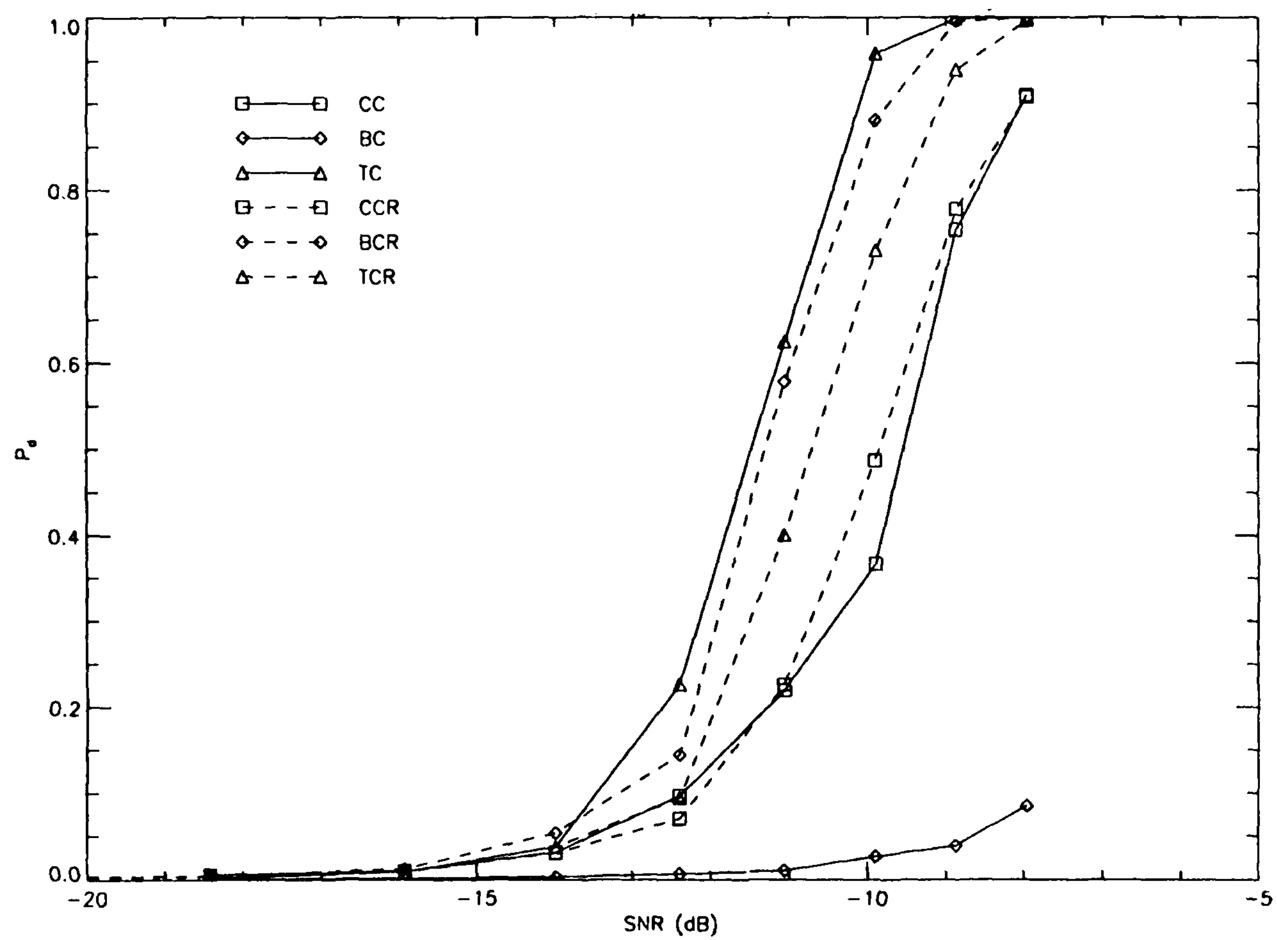


Figure 7. P_d versus SNR at $P_{fa} = 0.001$ for the 49 - 51 Hz sinusoid and an unknown source model.

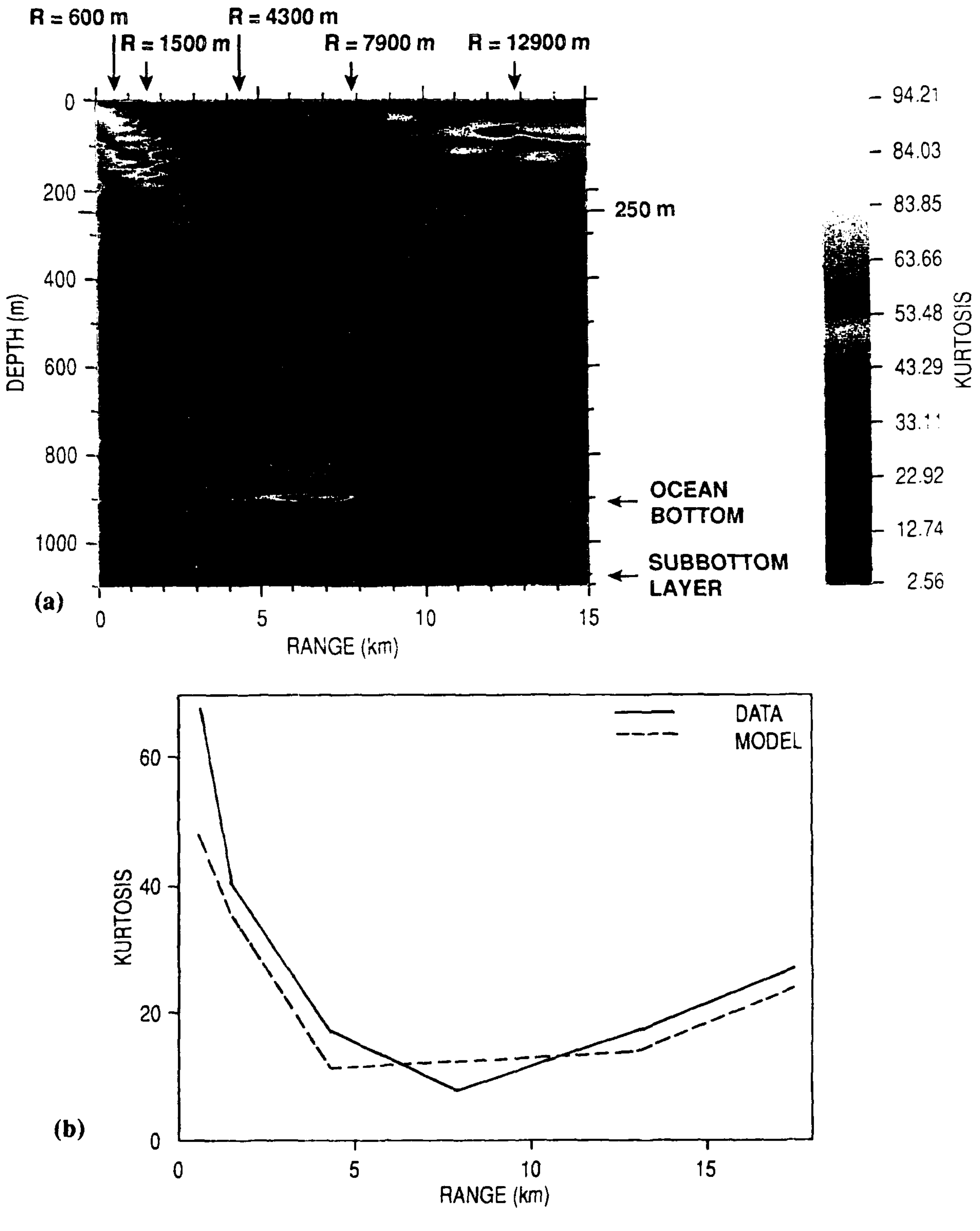


Figure 8. **(a)** Signal kurtosis over range and depth in a bottom-limited ocean environment. **(b)** Experimental data and TDPE model signal kurtosis at a depth of 250 m.

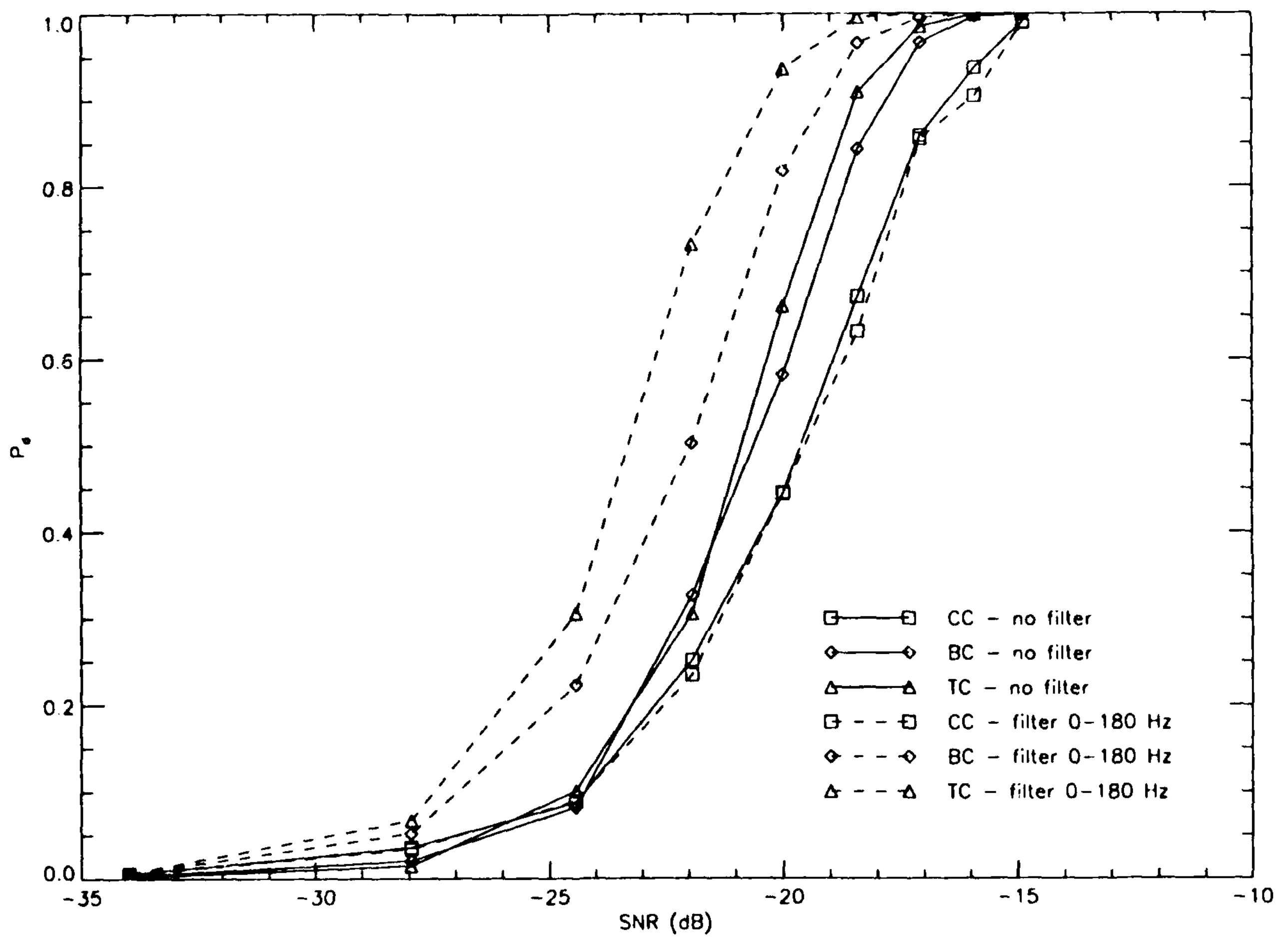


Figure 9. P_d versus SNR at $P_{fa} = 0.001$ for the narrow pulse and a known source model. Solid lines indicate no prefiltering. Dotted lines indicate prefiltering.

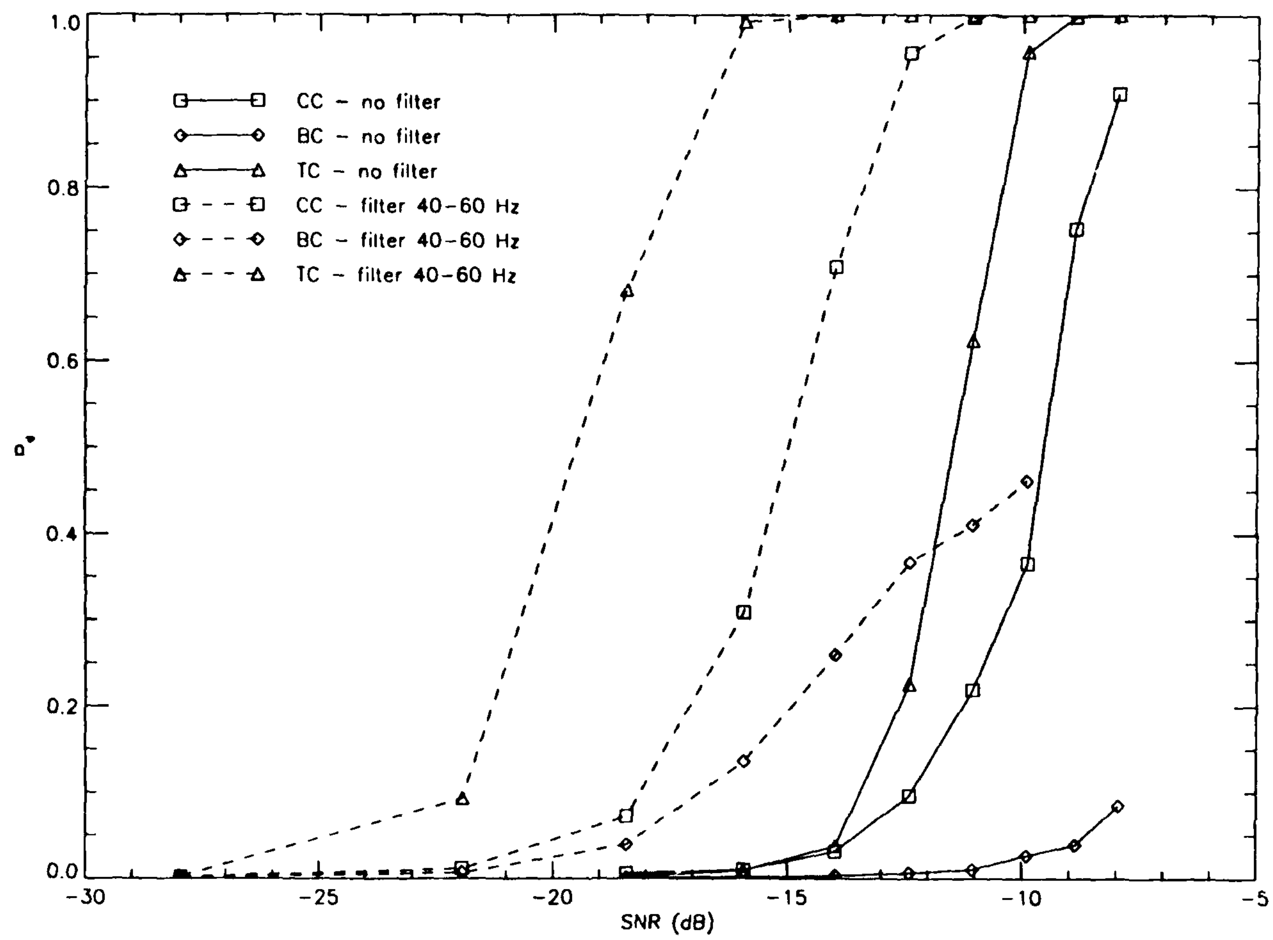


Figure 10. P_d versus SNR at $P_{fa} = 0.001$ for the 49 - 51 Hz sinusoid and a known source model. Solid lines indicate no prefiltering. Dotted lines indicate prefiltering.

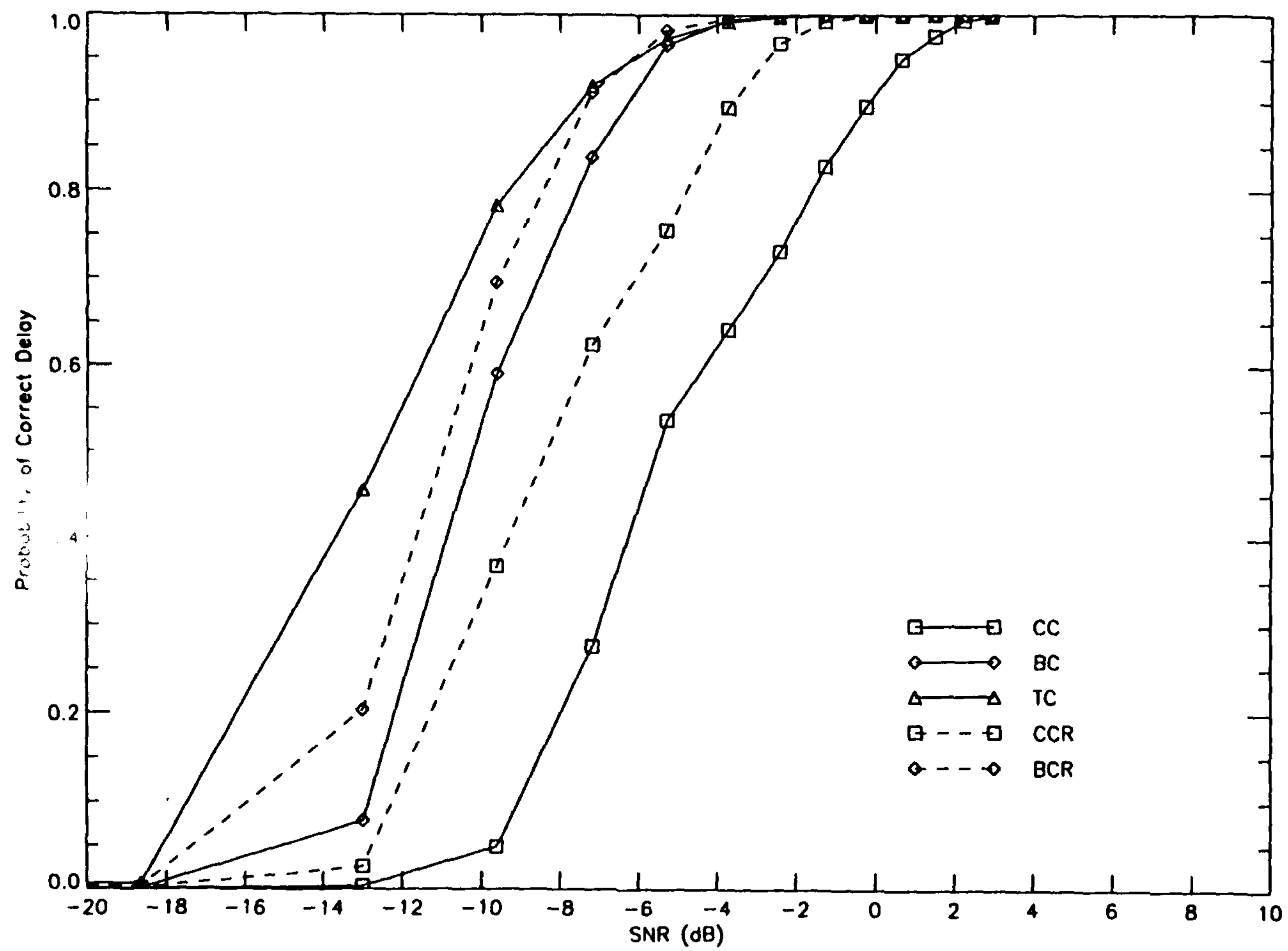


Figure 11. Probability of correct time delay estimation versus SNR for the narrow pulse and an unknown source model.

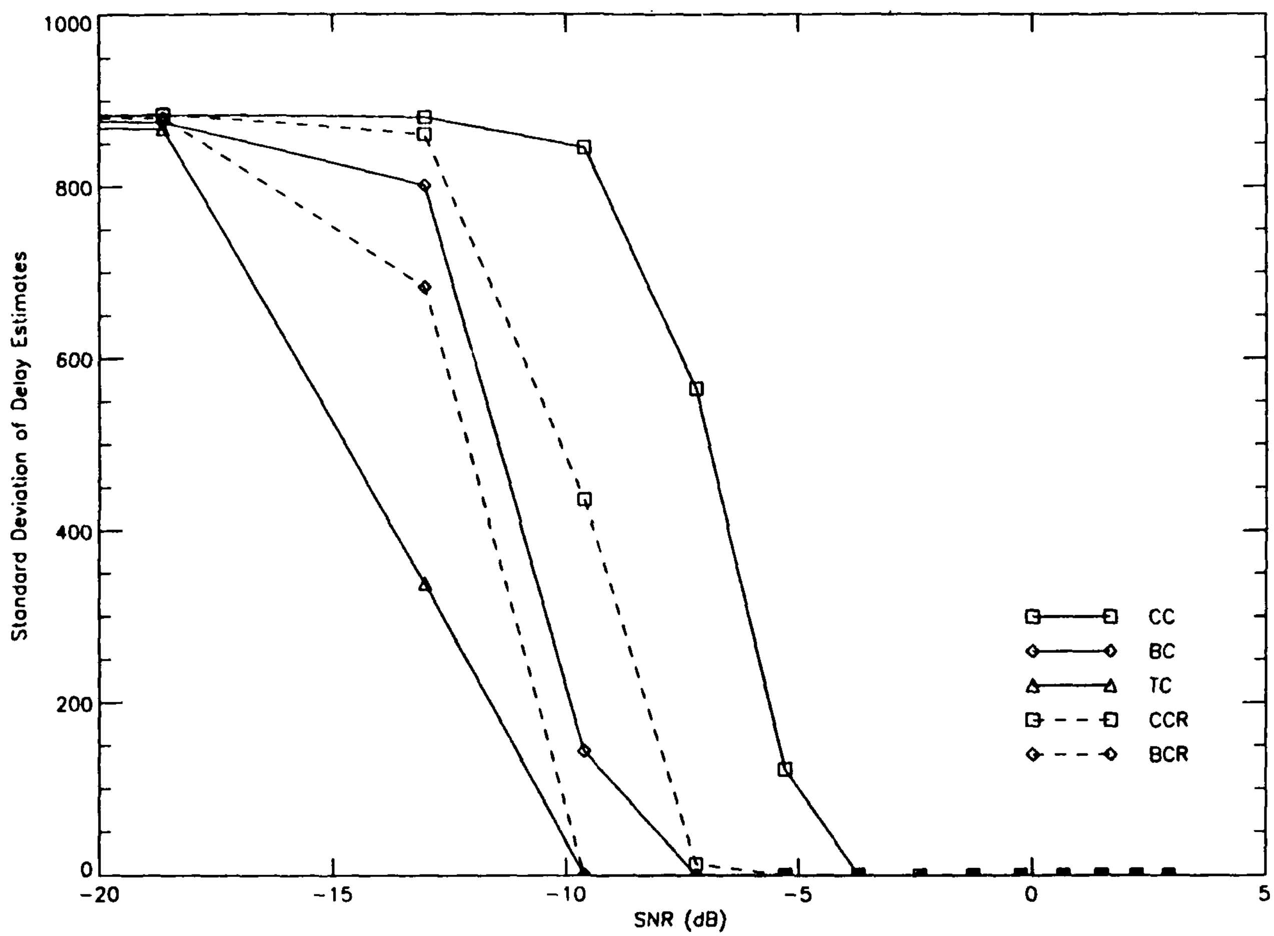


Figure 12. Standard deviation of all time delay estimates versus SNR for the narrow pulse and an unknown source model.